Simulation of Heat Extraction from Fractured Geothrmal Reservoirs(断裂型地熱貯留層からの熱抽出シミュレーションに関する研究)

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論文内容要旨

Hot Dry Rock (HDR) is a geothermal energy technology developed to harvest natural heat from the interior of the earth. HDR has some unique features in that the reservoir can be developed at any selected resource temperature giving the design increased flexibility. HDR reservoirs designs are also flexible in that the size can be selected; furthermore, the location, shape, and orientation of the engineered reservoir can be documented. A new concept of Hot Wet Rock (HWR) was put forward in order to connect a designed artificial crack with a pre-existing geothermal reservoir and take full advantage of the surrounding area which is full of potential thermal energy.

HDR/HWR field experiments of reservoir stimulation and circulation are expensive to perform and can not be repeated indefinitely from the same borehole due to progressive irreversible changes in the system under study. So, numerical experimentation provides a means to demonstrate understanding of the available experimental results and to extend that understanding to other conditions. Many numerical models have been made so as to obtain understanding of the HDR/HWR systems. Willis-Richards and Wallroth classified these models into three levels in their approach to the representation of the reservoir geometry; they are abstract model, reduced model and realistic model.

For *abstract model*, the geometry of rock mass is typically simplified into a rock lumped parameter. The *reduced model* explicitly simplifies the HDR systems to varying degrees, from one-dimensional (1-D) flow paths to two, three-dimensional (2, 3-D) regular fracture network. In order to reflect the fracture distribution of the HDR reservoirs, more realistic models have been proposed. In *realistic models*, the fracture is usually generated stochastically, and the probability distributions used to specify fracture orientation, density, and size have been chosen to fit the observations available.

However, as far as simulation is concerned, these models are as yet incapable of addressing many of the fundamental questions that face potential investors in a new and untried technology. This means that we are unable to describe the real system well enough to predict its long-term performance.

What kind of model do we expect?

The model must encompass our collective understanding of all the most important physics, geometry and processes active in such reservoirs, and are able to reflect and simulate the results of these processes. Furthermore, for an HDR model, what are important are not only the short term effects during reservoir stimulation, but also those which occur more gradually during long term circulation operation. Because the rock's dissolution and deposition and thermal contraction may have influence on the flow paths of the reservoir, the model should also incorporate these phenomena. Thus, the factors that we need to account for in the development of numerical model for fracture geothermal reservoir are:

1). Fracture shear and dilation during stimulation and circulation.

2). Chemical dissolution and precipitation during circulation.

3). Thermoelasticity during circulation.

One of the most important long-term factors influencing reservoir circulation could be chemical water/rock interaction such as dissolution and deposition. Although a full description of dissolution and deposition rates has not yet achieved, some efforts have been made to examine the effects of the chemical water/rock interaction using simple geometrical reservoir. However, 2 or 3-D models have not been developed to analyze the effect of chemical water/rock interaction on the long-term performance of HDR reservoir yet due to the lack of adequate data for reaction rates.

The thermoelastic effect on the long-term performance of HDR reservoirs is expected to be significant. One challenge in the development of HDR reservoir simulation models is to incorporate the effect of the thermoelasticity in a realistic fracture model. However, all the existing models used the reduced 1-D or 2-D models to examine the thermoelastic effect on the performance of reservoirs. It is difficult for these models to reflect the thermoelastic behavior of real HDR system due to the fact that the parallel plate or regular fracture distributions are an oversimplified description of the natural fracture system.

As discussed above, the effects of chemical water/rock interaction and thermoelasticity have not taken into account in the realistic model whose fracture distribution is similar to the real HDR fracture network.

In this study, a 3-D realistic model for the analysis of stimulation, circulation and thermal extraction from fractured geothermal reservoirs has been developed. In the numerical model, a fractal fracture network describes the distribution of natural joints in rock mass under consideration. Furthermore, the models are capable of incorporating the effects of the chemical water/rock interaction (dissolution and deposition) and the thermoelasticity due to the thermal drawdown in order to assess the long-term performance of engineered geothermal reservoirs. The on-going HDR geothermal energy extraction experiment, which is being performed in Hijiori, Yamagata Prefecture, Japan is simulated using the developed methods to predict the long-term fluid flow and production temperature variation.

The thesis consists of six chapters all together. ***Chapter 1*** describes the introduction.

In Chapter 2, simulation of reservoir stimulation and flow path, 3-D numerical simulation procedures of stimulation, fluid flow and tracer response at circulation stage were proposed for fractured geothermal reservoir systems. A method has been presented for determining the fractal fracture network which matches with the field observations. The distribution of fractal fractures within the Hijiori reservoir was determined by using a statistical approach generating 50 fracture patterns on the basis of the experimental data of RFR, reservoir shape delineated by microseismicity, flow rate and tracer response.

The RFR reflects the enhancement of fracture aperture in stimulation and the shape of reservoir reflects the characteristics of the fracture distribution in the reservoir.

The simulated results using the orientation of the natural fractures in the Hijiori field produced a value of RFR close to the field data. In addition, the numerical results showed that the shape of the simulated reservoir was close to that of the microseismic cloud of the Hijiori experiment, and reproduced the downward migration of the reservoir observed in the actual field.

The results of flow rate calculated from 50 simulations showed that the mean and mode value of the calculated flow rates were close to the field data for Hijiori. Then the agreement demonstrated the statistical approach employing the fractal fracture network model for predicting the flow rate before circulation. By defining error between the numerical and field results of the flow rate and tracer response, we selected suitable fracture patterns compatible with the field data.

The tracer response simulation showed that the calculated tracer response with a smaller total error was relatively close to the field data, and the agreement indicated that the present statistical approach could determine a suitable fracture network similar to that of Hijiori deep reservoir.

Thus, comparing these parameters (RFR, shape of reservoir, flow rate and tracer response) with those observed in the field, a numerical model of the Hijiori deep reservoir system that integrates many of the field observations and has stimulation and circulation properties that match the real system can be determined.

For the deep reservoir of Hijiori, a complete simulation of heat extraction has not been carried out yet. ***In Chapter 3***, simulation of heat extraction and its application to field experiments, a 3-D numerical procedure for calculating the heat transfer in fractured reservoir was presented. Then the numerical method, in conjunction with the simulation models mentioned in chapter 2, was used to simulate a short-term (25 days) heat extraction experiment conducted at Hijiori, and the models was also applied to predict the long-term production temperature history of the Hijiori deep reservoir. The simulated result was close to the 25 days heat extraction experiment of the Hijiori deep reservoir, indicating the usefulness of the 3-D model in predicting the heat extraction characteristics.

The simulated long-term temperature histories showed that the details of the flow path greatly affected the production temperature and heat extraction, and that the temperature results with the smaller total error produced no significant difference. This may suggest the potential of predicting the long-term performance using the present simulation models. For the existing Hijiori deep reservoir, it appeared that the fracture system created in Hijiori deep reservoir might be insufficient in terms of the magnitude area for commercial HDR designs.

In Chapter 4, effect of chemical water/rock interaction on heat extraction, the chemical water/rock interaction was incorporated into the 3-D thermal extraction simulations to examine the influence of the chemical water/rock interaction on the long-term performance of Hijiori deep reservoir.

The calculated result showed that the injection flow rate increased with the increase of time, and this suggested that the aperture widening due to dissolution may play a dominant role in the flow characteristics rather than precipitation at the Hijiori deep reservoir. The simulated results suggested that larger flow rate and higher initial temperature of reservoir might exert the obvious effect of the chemical water/rock interaction due to the enhanced rock dissolution.

For the Hijiori deep reservoir, however, the chemical water/rock interaction was expected to have little effect on the long-term performance due to the small flow rate in fracture network. The injection flow rate had increased only by 0.5 %, and the production temperature kept almost the same temperature history as the one without considering the chemical water/rock interaction for 1500 days. Thus the influence of the chemical water/rock interaction on permeability of the reservoir might not be significant.

In Chapter 5, effect of thermoelasticity on heat extraction, a simplified thermal stress model was introduced in order to incorporate the effect of thermal contraction in the 3-D fractured reservoir model.

The simulated results for Hijiori deep reservoir showed that the thermoelasticity exerted the great effect on the long-term performance of Hijiori deep reservoir. The injection flow rate increased by 20% and this was accompanied by 8% decrease in water loss. This effect increased with the increase of initial rock temperature and injection flow rate. The production temperature dropped about 100 ℃ for 1500 days due to the influence of thermoelasticity.

Comparing the effect of the chemical water/rock interaction with thermoelasticity, the thermoelasticity was confirmed to be the major factor which cause the change of the long-term performance. Thus, the thermoelasticity was suggested to play a predominant role on the thermal short circuit formation in the future operation of the Hijiori deep reservoir.

Although the chemical water/rock interaction and thermal stresses exerted very different influence on the long-term temperature and flow rate history, the two effects resulted in the production of the similar thermal energy output in spite of the different injection pressure and initial rock temperature.

The main conclusions are summarized ***in Chapter 6***.

審 査 結 果 の 要 旨

水圧破砕を用いる次世代型地殻エネルギー抽出技術の開発には、長期の抽熱性能を予測するための学術的基礎の確立が必要不可欠である。これまで、単一き裂型地熱貯留層については水圧破砕および熱抽出挙動の解析法が開発されているものの、断裂型地熱貯留層からの抽熱を予測するための方法論については未だ確立されていないのが現状である。

本論文は、断裂型地熱貯留層を対象として、地下き裂分布の推定法ならびに水圧破砕、循環および長期熱抽出の数値シミュレーション法の開発を行い、肘折のフィールド実験へ適用したもので全編6章よりなる。

第1章は序論であり、本研究の背景を述べている。

第2章では、岩体中の天然き裂分布を特徴づける手法としてフラクタルき裂モデルを用い、水圧破砕、循環挙動ならびにトレーサー応答を評価するために開発した3次元数値シミュレーション法について説明している。次に、実フィールドのボアホールを用いた計測結果に適合する地下き裂分布を抽出するための統計的手法を考案し、本法を肘折で得られた計測結果に適用することにより同フィールドで作成された人工地下き裂の分布を推定している。さらに、提案した手法を用いて、異なる流量で実施された循環試験結果を予測できることを示し、推定した地下き裂分布の妥当性を与えている。これは実用上有用な新しい提案である。

第3章では、推定した人工地下き裂分布に基づき循環時の3次元熱移動解析を行い、30日間の短期循環試験で得られた熱水温度を予測できることを示し、本熱移動解析法が抽熱性能の予測に有効であることを検証している。

第4章では、長期循環に伴う岩石-熱水間の化学的相互作用の影響を考慮し、岩石の溶解・沈積速度の計算と流体・熱移動の計算とを連成させた数値解析法を開発し、通水特性の化学的相互作用による経時変化を予測するための手法を提供している。

第5章では、抽熱に伴う岩体の熱収縮の影響を考慮するために、単純化した熱応力モデルに基づく熱抽出シミュレーション法を開発し、長期抽熱性能を予測するための計算方法を提案している。また、本法を用いることにより、肘折フィールドの長期抽熱性能に関しては岩体の熱収縮の影響が溶解・沈積の影響に比較して大きいことを示唆している。これは注目すべき知見である。

第6章は結論である。

以上要するに本論文は、断裂型地熱貯留層を対象として長期抽熱性能の設計を目的とした水圧破砕・循環・熱抽出の3次元数値シミュレーション法を提案したものであり、機械工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。